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EXPERIMENTAL AND NUMERICAL HEAT TRANSFER ANALYSIS ON MIXED MODE SOLAR CROP DRYER

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ABSTRACT

The present work explains the design, fabrication, and analysis of solar dryer with heat storage material. The mild was used as the heat storage material. By using the basic theory of energy balance, the numerical heat transfer analysis is made for the performance of the collector and comparison between experimental and numerical methods for the efficiency is described. The process of drying phenomenon is explained with the help of characteristic curves. The product used during the experiments was 4 kg chilly, 2 kg in the upper tray and 2 kg in the lower tray. The drying time required for the chilly at upper tray to reach safe moisture content level is 7 hours and chilly at lower tray had taken 8 drying hours to reach the safe moisture content. The maximum drying rate reported is 14.345 grams/minute and the minimum value is 0.898 grams/ minute. The maximum value of theoretical efficiency reported is 24.191 % and the minimum is 22.8 % whereas the maximum value of actual efficiency obtained is 17. 88 % and the minimum is 6.9 %.

KEYWORDS: Heat Transfer, Crop, Chilli, Solar & Dryer

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Original Article

1. INTRODUCTION

In the present days the world's demand for food requirement increases rapidly due to population explosion, urbanisation and change in eating habits of the people The increase in food demand can be effectively met by bringing more land for agriculture, incorporating modern technology and machinery in agricultural sector, developing fast-growing crops, controlling increase in population and by avoiding loss of food during post-harvesting period. In developed countries, the modern technologies are used during the harvesting and storage food crops and loss food crops during harvesting storage are minimum whereas in developing countries due to lack of modern technologies and storage facilities the loss in food crops is high. A Study shows that loss of post -harvesting food products is high in developing countries and annual food loss is estimated is around 30 percent of cereals, 40 –50 percent of root crops, fruits and vegetables, 20 percent of oilseeds, meat and dairy products, and 35 percent of fish [1]. To grow food crops, it is required to consume resources like fresh water, agricultural land, fertilizer, pesticides, human work, and mechanical energy. The loss of food products results in the waste of all these useful resources [2]. The loss of food crops can be reduced effectively by developing advanced technologies the harvesting and storage of food crops. If the technologies are developed to reduce the loss of food products, it indirectly saves other resources and helps to achieve food security. Solar crop drying is an application of solar energy used to reduce the loss of food products during post-harvesting time. The solar crop drying is best suitable for developing countries, where enough cold storage facilities are not available for

storage purpose. General crop drying method followed is by spreading product over a platform or plane surface and crop is directly exposed to the sun's rays, moisture evaporation takes place due to the energy of sun's radiation and flow of ambient air over the crop surface. This method of drying is called as open sun drying or natural drying. The open sun drying is a simple and economical method but it has many disadvantages namely; no control over the drying rate, attack by birds and animals, dust and other particles may mix with the product, sudden rain may cause damage [3]. To reduce the disadvantages of open sun drying, solar crop dryers are being developed. Solar dryers are mainly classified into three types; direct mode solar dryers, indirect mode solar dryers and mixed mode solar dryers. In direct mode solar dryers, solar radiation is directly incident on the product through a glass cover, in indirect mode dryers, atmospheric air is heated by a separate collector (air heater) and then heated air allowed to enter the closed drying chamber and mixed mode dryers combines the features of direct mode and indirect mode dryers. Selection of a dryer depends on the parameters like a physical characteristic feature of the dryer, thermal performance, the crop being handled, drying characteristics of the crop material, product qualities, facilities available at the site of proposed installation and economics [4].

The researchers have been trying to develop new solar dryers with modern technology. Before the development of dryer, it is essential to understand the open sun drying process. A study on open sun drying is conducted[5] and discussed thermal aspects of open sun drying of various crops like green chilies, green pea, onions, potatoes, and cauliflower and it reported that, the convective heat transfer coefficient for varied significantly with the type of crop. This is because the porosity, shape, size and initial moisture contents of the crops are not the same for all the crops. The temperature required for the crop drying process in not high, for example, maximum allowable drying temperature for Corn is 68 ^{0}C – 80 ^{0}C, Bananas is 70 ^{0}C [6]. The direct mode solar dryers are easy to fabricate and the materials at the local market are sufficient to fabricate a dryer. The direct mode dryers were developed by using locally available materials for drying grains [7], the materials used were plywood, perplex glass, wire mesh angle iron and similar type of direct mode dryers are developed for drying of yam crop [8], fishery products [9] and tropical crops [10].

For photosensitive crops, it is not recommended to expose crop directly to the sun's rays, because this causes loss of important nutritious contents from the crops. Thus for photosensitive crops, indirect mode dryers are preferable. In the indirect type of dryers, a separate collector is used to collect solar energy. Some important materials used for the construction of collector are gravels [11], vacuum tube [12] for chilies drying, sand bed[13] and phase change materials for drying grapes [14]. Mixed mode dryer for drying of Yam's chips has been developed by using 2mm aluminum sheet for absorber material and well-seasoned wood for cabin material [15]. Similar dryer type of dryer with an iron sheet as the absorber material was proposed for the drying of Cuminum grains [16]. Researchers were tried to improve the performance of dryers by using simple techniques like pebbles (heat storage material) coated with black [17] and pebbles coated with black [18]. In one study used SAE 20/40 oil is used as a heat storage material for mixed mode dryer [18]. A cylindrical glass dryer with flat plate collector (Air heater) made of galvanized steel sheet as absorber) is developed [19] and the advantage is cylindrical glass drying chamber receives sun's rays from all the directions without any tracking mechanism. Mathematical and numerical model analysis to understand drying phenomenon carried out for the drying models of cylindrical tunnel type [20], direct mode, indirect mode and mixed mode type of dryers [21].

The objective of the present work was to develop a mixed mode solar crop dryer with heat storage materials and to study the phenomenon of drying.

2. MATERIALS AND METHODOLOGY

2.1 Design and Fabrication of Experimental Setup

The complete experimental setup is fabricated by using the materials available at the local market of Ujire, Karnataka, India. The dryer cabin is made of GI sheet, two iron mesh trays were used to keep the products to be dried and inlet and outlet vents are provided at the bottom side and top side for air flow. A glass cover is provided at top of the dryer cabin and the insulation is provided by thermocoal. Mild steel materials with T-shaped arrangements were filled in the solar collector cabin. The collector cabin is made of well-seasoned wood and wood acts as the insulation material. Figure 1 shows the pictorial diagram of collector cabin filled with mild steel materials. A transparent glass cover is provided at the top of the collector to avoid the re-radiation losses. The dimensions of the dryer cabin and collector cabin are maintained symmetrically [22]. The slope of the glass cover and cabin are made to equal to the latitude of the location [23] i.e. slope maintained is 13^0 (Latitude of Ujire, Karnataka, India is 12.99^0 N). The collector and dryer cabins are connected by hose pipes. Figure 2 represents the pictorial diagram of the fabricated experimental setup.

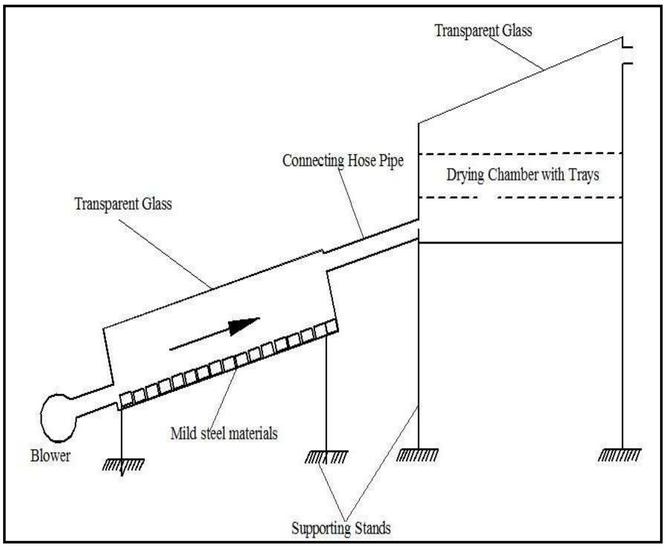

Figure 1 Schematic Diagram of the Experimental Setup

Figure 2 Pictorial Diagram of the Experimental Setup

2.2 Experimental Procedure

Prior to the experiments, the drying system was checked for the air gaps and instrumentation. Then the two trays were loaded with 4 kg of chily i.e. 2 kg in each tray. The experiments were started at 9:00 o'clock and stopped when the product reaches the safe moisture content. During the experiments chily was used and the recommended safe moisture content for the chilly is below 10 % on wet basis. For every one hour interval readings were recorded. Temperature was measured with calibrated thermometers, weight of the chily was measured with calibrated digital weighing balance and solar radiation flux was measured by a digital pyranometer.

2.3 Experimental Analysis

The experimental analysis gives information about actual performance of the drying system. The following correlations were used for experimental analysis.

2.3.1 Determination of Overall Thermal Efficiency of the Dryer

To find the thermal efficiency of solar collectors two methods are used; the instantaneous method and the calorimetric method. For testing of solar collectors, the instantaneous method is widely used. The equation (1) represents the thermal efficiency of the solar collector by an instantaneous method.

$$\eta_H = \frac{m\ Cp\ (To - Ti)}{I\ A + P} \tag{1}$$

In equation (1), m is the mass flow rate of air in kg/s, C_p is specific heat of air in J/kgK, T_i and T_o are air inlet and outlet temperatures in ^{0} C, I intensity of solar radiation in W/m^{2,} A is gross area of heat storage cabin in m^2 and P is power required for blower.

2.3.2 Determination of Moisture Content

To find the moisture content of a product two methods are used, wet basis method and dry basis method. Most of the researchers have been used wet basis method. The equation (2) gives a correlation to calculate moisture content based on a wet basis.

$$M_{WB} = \frac{(M - Md)}{M} \times 100 \tag{2}$$

In equation (2), M_{WB} is moisture content, M is weight at any given drying period and M_d is water free weight. An electric oven method is used to find the dry bone weight of the product.

2.3.3 Determination of Drying Rate

Drying rate is the amount of moisture evaporated from a product for given drying time. Equation (3) represents the rate of moisture evaporated.

$$DR = \frac{dm}{dt} \tag{3}$$

In equation (3), dm is the difference in weight and dt is time period.

2.3.4 Determination of Heat Energy Used

The heat energy used to evaporate the moisture from a product is calculated by using equation (4)

$$Q = (M_0 - M)\ h_{fg} \tag{4}$$

In equation (4) W_0 is the initial weight of the product, M is the final weight of the product and h_{fg} is latent heat of vaporization of water.

2.3.5 Determination of Relative Humidity (Φ)

The relative humidity is the ratio the mass of water vapor to the mass of saturated water vapor in the same volume at the same temperature. The correlations (5) and (6) are used to find the relative humidity.

$$Pv = (Pvs)WBT - ((P - (Pvs)WBT) - (DBT - WBT))/(1427 - 1.44\ WBT) \tag{5}$$

$$\Phi = (Pv)/PVS \tag{6}$$

2.4. Numerical Heat Transfer Analysis on Heat storage Cabin

For the numerical heat transfer analysis of heat storage collector, the following correlations were used. The correlations are referred from solar energy [23] and heat transfer textbooks [24]. According to the experimental setup the suitable modifications are also made in the correlations.

2.4.1. To Find the Temperature of Absorber Pate Following Correlation was Used

$$\left(\frac{q}{A}\right)(\dot{\alpha})_1 = (\dot{\alpha})_2\, \sigma\, (T_a^{\,4} - T_s^{\,4}) \tag{7}$$

where Ta is absorber plate temperature, T_s is surrounding temperature

For Mild steel $(\dot{\alpha})$ is 0.37 and $(\dot{\alpha})_2 = 0.6$ (Radiation properties of steel)

2.4.2. Characteristic Length (Lc)

$$Lc = \frac{4Ac}{P} \tag{8}$$

Ac is duct area in m^2

P is perimeter in m

2.4.3. Reynold's Number

$$Re = \frac{Lc\ u}{v} \tag{9}$$

u is air velocity in m/s

v is kinematic viscosity

2.4.4. Nussult Number (Nu)

$$Nu = 0.023\ Re^{0.88}\ Pr^{0.33} \tag{10}$$

Pr is Pradntle number

2.4.6. Convective Heat Transfer Coefficient (h)

$$Nu = \frac{hLc}{k} \tag{11}$$

$$h = \frac{Nuk}{Lc}$$

2.4.7. Convective Heat Transfer Coefficient between Topmost Cover and the Surrounding Air (hw)

$$hw = 5.7 + 3.8\ Vw \tag{12}$$

Vw is average wind speed in m/s

2.4.8. Bottom Lose Coefficient (Ub) L_1

$$\mathrm{Ub} = \frac{\mathrm{ki}}{\delta} \tag{13}$$

ki is the thermal conductivity of insulating material and δ is the thickness of insulation in m.

2.4.9. Side Loss Coefficient (Us)

$$\mathrm{Us} = \frac{(\mathrm{L-W})\mathrm{H\,ki}}{\mathrm{L\,W\,\delta}} \tag{14}$$

L is the length of the collector is the width of the collector, H is the height of the collector and δ is the thickness of insulation in m.

2.4.10. Top Loss Coefficient (Ut)

$$\mathrm{Ut} = \left[\frac{M}{\left(\frac{C}{Tp}\right)(Tp-Ta)(M+f)0.252} + \frac{1}{\mathrm{hw}}\right]^{-1} + \left[\frac{\sigma(\mathrm{Tp2+Ta2})(\mathrm{Tp-Ta})}{\frac{1}{\left(\varepsilon\mathrm{p}+0.0425\mathrm{M}(1-\varepsilon\mathrm{p})\right)+\left(\frac{2\mathrm{M+f+1}}{\varepsilon\mathrm{c}}\right)-\mathrm{M})}}\right]^{1} \tag{15}$$

$$\mathrm{f} = \left[\frac{9}{\mathrm{hw}} - \frac{30}{\mathrm{hw}^2}\right] - \left[\frac{\mathrm{Ta}}{316.9}\right](1+0.091\mathrm{M})$$

$$\mathrm{C} = 204.429\,(\cos\beta)^{0.252}/\mathrm{L}^{0.24}$$

εp is emissivity of the heat storage bed

Tp is heat storage material surface temperature

εc is emissivity of the glass cover

2.4.11. Overall Loss Coefficient (U_L)

$$\mathrm{U_L} = \mathrm{Ut} + \mathrm{Ub} + \mathrm{Us} \tag{16}$$

2.4.12. Radioactive Heat Transfer Coefficient (hr)

$$\mathrm{hr} = \frac{\sigma}{\left[\frac{1}{\varepsilon\mathrm{p}}+\frac{1}{\varepsilon\mathrm{c}}-1\right]}\;\frac{(\mathrm{Tp}^4-\mathrm{Tc}^4)}{(\mathrm{Tp-Tc})} \tag{17}$$

2.4.13. Equivalent Heat Transfer Coefficient (he)

$$\mathrm{he} = \mathrm{h} + \frac{\mathrm{h\,hr}}{\mathrm{h+hr}} \tag{18}$$

2.4.14. Collector Efficiency Factor (F)

$$\mathrm{F} = \left[1+\frac{\mathrm{Ul}}{\mathrm{he}}\right]^{-1} \tag{19}$$

2.4.15. Collector Heat Removal Factor (F_R)

$$\mathrm{F_R} = \mathrm{x}(1-\mathrm{e}^{-\frac{1}{\mathrm{x}}}) \tag{20}$$

$$x = \frac{mCp}{UL\ AC}$$

Where m is mass flow rate

Cp is the specific heat

A_C is Collector

2.4.16. Useful Heat Gain

$$q = F_R\, Ac\, [I(\tau \propto) - Ul(Tp - Ta) \quad (21)$$

where τ is transitivity of the glass cover

∝ is absorptivity of heat storage material

2.4.17. Instantaneous Collector Efficiency

$$\eta = \frac{q}{I\ AC} \quad (22)$$

3. RESULTS AND DISCUSSIONS

In this section, the results obtained are discussed with the help characteristic graphs. Figure 1 shows the graph of drying time and product moisture content, it is observed that the product at the upper tray reaches safe moisture content with 7 hours of drying and the product of lower tray had taken 8 drying hours to reach the safe moisture content level. The product of upper tray receives direct sunlight along with hot air circulation and always there is a presence of shading effect on the lower tray by the upper tray and hence the product of the lower tray required one hour extra drying time. The rate of drying is a useful parameter used to study the performance of the dryer. Figure 4 shows the graph of drying time and drying rate. From Figure 4 it is observed that, the drying rates are high during the initial drying periods and reaches the peak value, this is because the product contains more amount of moisture at their outer layers. After the value of peak drying rate, the amount of water present at the outer layer is small and inner layer contains more amount of water during this period and it takes time to reach to the outer layer through the diffusion process and therefore drying rates are low during the end periods of drying. The maximum value of drying rate obtained is 14.345 grams/minute and the minimum value is 0.898 grams/ minute.

The advantage of using air heaters with drying is the relative humidity of the air at the air heater outlet is small and hence the more amount moisture extraction is possible in the dryer cabin. Figure 5 shows the variation of the relative humidity of the air. From the figure 5, it is observed that the relative humidity of the air at collector outlet (heat storage material cabin) is much lower than the relative humidity of the atmospheric air and therefore the water absorbing capacity of the air increases and these results in higher drying rates.

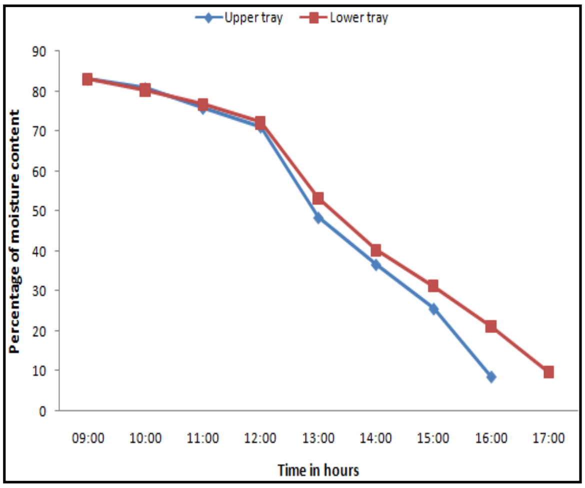

Figure 3 Time v/s Percentage of Moisture Content

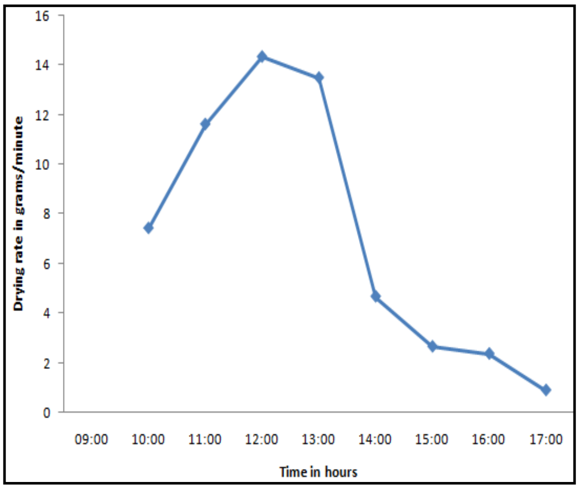

Figure 4 Time v/s Drying Rate

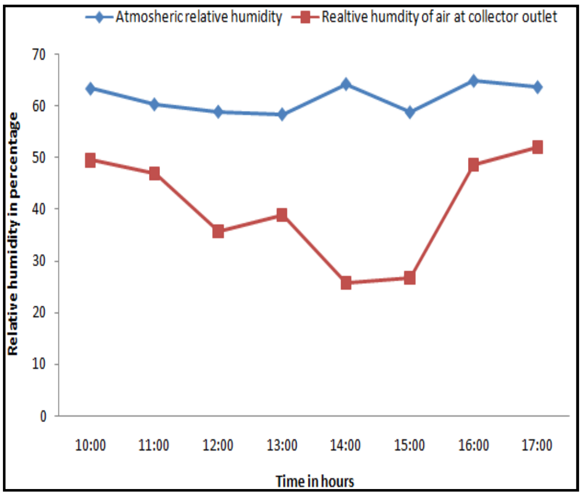

Figure 5 Time v/s Relative Humidity

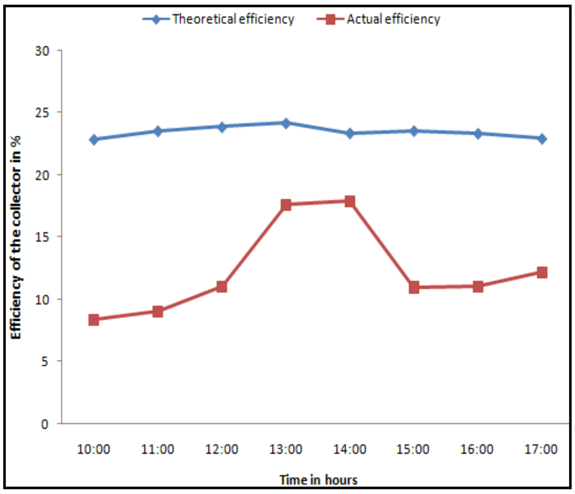

Figure 6 Time v/s Collector Efficiency

The experimental and theoretical efficiency of the collector cabin is shown by Figure 6. The actual efficiency of the collector is less than the ideal or theoretical efficiency. The difference in efficiency due to the fact that, in the theoretical analysis many assumptions were made like the temperature of the heat storage bed is uniform, the outlet air temperature is equal to bed temperature of the heat storage material. But practically many parameters affecting the performance of the dryer and it is difficult to consider all the parameters in the practical analysis. The theoretical efficiency of the collector is almost constant whereas the actual efficiency of the collector varies significantly. The maximum value of theoretical efficiency reported is 24.191 % and the minimum is 22.8 % whereas the maximum value of actual efficiency obtained is 17. 88 % and the minimum is 6.9 %.

Figure 7 represents the overall efficiency of the dryer. During the initial periods of drying, the energy used for the evaporation moisture is less and increases as the drying time proceeds. The efficiency of the dryer increases as the amount of energy collected is used to remove the moisture. During the periods of end drying, the water present in the product is less and the energy utilized to remove this moisture is also less and therefore the dryer efficiency decreases during the end periods. The maximum value of dryer efficiency obtained is 52.11 % and the minimum value is 3.66 %. The variation of the solar radiation flux is shown in figure 8. The solar radiation fluxes are minimum during the morning time and increases

in the noon time and start decreasing during the evening time. This variation of solar radiation flux affects the performance of the dryer system. The variation drying rate and efficiency of the collector and dryer follow the same pattern of the solar radiation flux. Therefore the drying process mainly depends on the availability and nature of solar radiation and therefore the day with clear sunshine results in better performance.

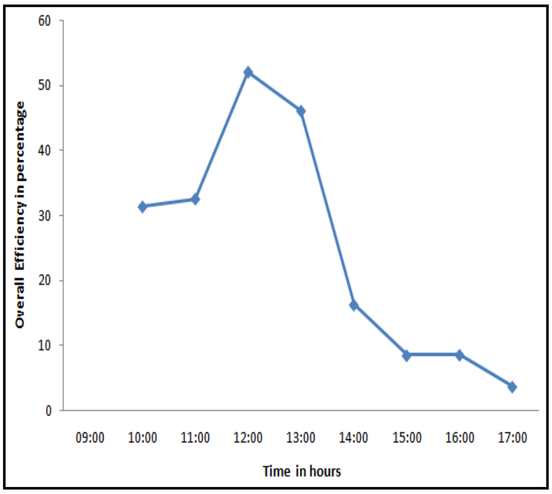

Figure 7 Time v/s Overall Dryer Efficiency

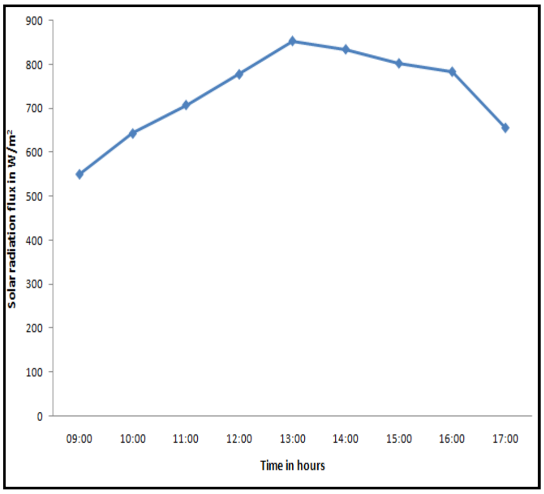

Figure 8 Time v/s Solar Radiation Flux

4. CONCLUSIONS

The present work explains the design, fabrication and the analysis of a mixed mode solar dryer with heat storage materials. Mild steel was used as heat storage material in the collector and numerical analysis is made by using a basic energy balance method. The study shows that use of heat storage materials helps to improve the performance of the dryer. The comparison of experimental and numerical efficiency of the collector is explained. The behavior of the drying phenomenon is explained with the help of characteristic curves.

The drying time required for the upper tray chilly to reach safe moisture content level is 7 hours and chilly at lower tray had taken 8 drying hours to reach the safe moisture content. The maximum drying rate reported is 14.345 grams/minute and the minimum value is 0.898 grams/ minute. The maximum value of theoretical efficiency reported is 24.191 % and the minimum is 22.8 % whereas the maximum value of actual efficiency obtained is 17. 88 % and the minimum is 6.9 %.

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